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POTENTIAL OF OPTICAL FOURIER ANALYSIS FOR MEASURING WINDSCREEN --ETC(U)
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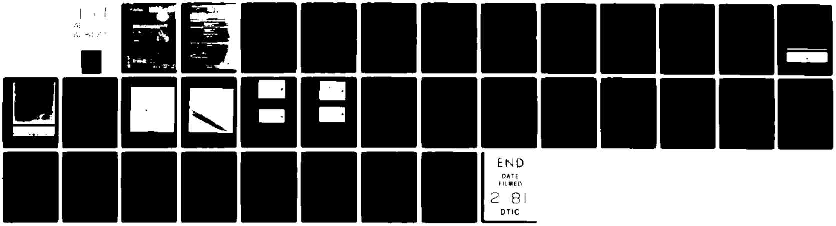

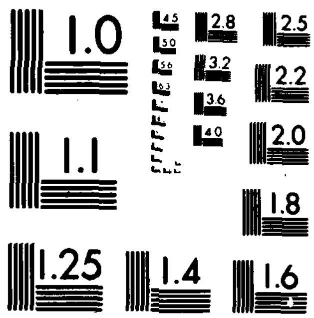

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The potential of an optical Fourier technique for measuring the optical distortion of aircraft windscreens was examined. It was hypothesized that the compactness of the harmonics of the optical Fourier transforms of vertical and horizontal square wave targets photographed through windscreens would correlate highly with distortion in photographs of a gridboard. Eleven transparent optical distortion panels were used to produce gridboard pictures and vertical and horizontal transform pictures. Gridboard pictures were subjectively ranked by 23 observers for amount of optical distortion. (continued)

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Transform pictures were ranked for compactness of the third harmonic. All three picture sets were also measured by subjective magnitude estimation.

Rank correlation between gridboard photograph distortion ranks and compactness ranks for the vertical Fourier transform was .950. Overall rankings of gridboard distortion photographs and compactness rankings was .977. Such high statistically significant correlations show that distortion judgements from gridboard photographs is accurately predictable from judged compactness of the third harmonic. Thus, the Fourier method may be useful for measuring optical distortion. Development of objective methods to measure the compactness and to calibrate such measures against conventional measurements is warranted. This development would lead to a rapid, accurate and objective method for measuring the optical distortion of aircraft windscreens.

PREFACE

This report was prepared in the Human Engineering Division of the Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio. The work was performed under Project 7184, Man-Machine Integration Technology, Task 18, Visual Effects of Windscreens on Pilot Performance, and Work Unit 03, Visual Perception Through Windscreens. This work supports the Improved Windscreen Protection Development Program, Projects 2202 and 1926 of the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio.

The authors thank Mr. Mike Pool and Mr. Allen Pinkus for constructing the light box for the targets, constructing the target patterns and doing the photography.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

Aircraft windscreens are optical devices through which the pilot observes the environment outside the aircraft. As aircraft speeds have increased and operational altitudes have been lowered to several hundred feet above the ground, the impact on aircraft windscreens has been significant. The windscreens have been designed as smoothly curved surfaces installed at extremely slanted angles to reduce aerodynamic drag and improve operational performance. Because of the lower operating altitudes, the probability of an aircraft colliding with birds has increased. The windscreens are therefore designed to be thick enough, and the material they are made of tough enough, to withstand these impacts with birds, usually called "bird strikes." The result of these evolutionary changes is that the windscreens are being designed as thick, curved sections of multilayered plastic to achieve the desired aerodynamic and bird strike resistant characteristcs. This has recently led to increased concern about the see-through optical distortion quality of the windscreens.

Optical distortion assumes many forms, such as magnification which varies from point to point on the windscreen, images optically displaced by variable amounts and variable directions from point to point in the field of view, etc. In non-quantitative terms, a windscreen (or any transparency) is said to have distortion if a straight line target pattern appears curved or wavy when viewed through the transparency. The basic problem is to define this effect in such a way that it may be quantified and measured. Probably the most widely used definition of distortion (for aircraft windscreens) is "distortion is the rate of change of deviation" (Thompson; 1970), (Grether; 1973). However, it has also been defined as "...a *nonuniform* rate of change of deviation..." (Cocagne & Blome; 1968). In each of these, deviation is defined as the angular change that a light ray undergoes in passing through the transparency.

Distortion has also been categorized into loosely defined types such as banding, sharp bending, blurring, bull's eyes, convergency, magnification and rolling (Thompson; 1970, Self; 1976). An attempt at defining distortion in terms that could be used for accepting or rejecting aircraft windscreens was made by Thompson (1970) in conjunction with the F-111 glass windscreens.

The problem is to devise a relatively rapid and accurate method to measure the quantitatively defined parameter of distortion. This might be done by a direct method or by a measure that indirectly represents the effects of distortion. A second very important aspect of the problem, in either case, is to validate any direct or derived measurements by comparisons with (1) judgments of distortion in the same windscreens by human observers or (2) conventional measurement methods. This must be done in such a way that limits on the measured parameters can be set for acceptance or rejection of the windscreen. This problem is compounded by parameter value changes of most measures with changes in viewing position and field angle.

METHODS OF MEASURING DISTORTION

Most methods of measurement currently in use require that a photograph be taken through the windscreen of a large, high contrast target pattern made up of a rectilinear matrix of one inch squares, using line widths of either 1/32 or 1/16 inch. These target patterns are usually made by constructing a string board with numerous horizontally and vertically oriented strings spaced one inch apart. A variation of this is to use a spacing of ½ inch as a means of improving the sensitivity of the distortion measurements. The influence of gridboard line width and spacing on windscreen distortion measurements is discussed by Seid and Self (1978). Similar target patterns have also been constructed using photographic transparencies or painted grid masks on glass or clear plastic in front of a source of back illumination in a light box. The most widely used target has white lines against a dark background, although some have been built with a reverse polarity.

GRID LINE SLOPE

This measurement is probably now the most popular. A photograph is taken of the target board through the windscreen. The camera is located at the design eye position of the windscreen (Douglas Report; 1975) or at some other designated distance from the windscreen (ASTM; 1976). The windscreen distance from the target gridboard is determined by the specific desires of those requiring the test. It is sometimes determined by the size of the room available for testing. The effects of variation in these distances on gridboard magnification produced by windscreen focusing power are analyzed by Seid and Self (1978). Figure 1 shows the photographing geometry. Care is taken to insure that the film plane of the camera is parallel to the plane of the gridboard. Also, a low distortion lens is required for the camera, and later, for the photographic enlarger that makes the large prints. The resulting photograph is enlarged, usually to 8 by 10 inches, for measurement. The photographic enlargement or print is then placed on a drafting board and aligned so that some of the horizontal grid lines recorded around and outside the edge of the windscreen are accurately horizontal on the table. These lines are not distorted by the windscreen, and therefore may be used as a baseline reference. Once the photograph has been aligned, it is firmly fixed to the table with masking tape. Then a drafting square is used to determine the magnitude of the slope of any lines that deviate from perfectly vertical or perfectly horizontal. The photograph is measured in several areas to determine the maximum slope. The slope is usually given as a ratio, such as 1 in 20 or 1 in 10, which is the tangent of the angle between the horizontal or vertical, whichever is being measured, and the straight lines showing at the sides of the picture. Table 1 compares different distances and units that have been used or proposed by different organizations.

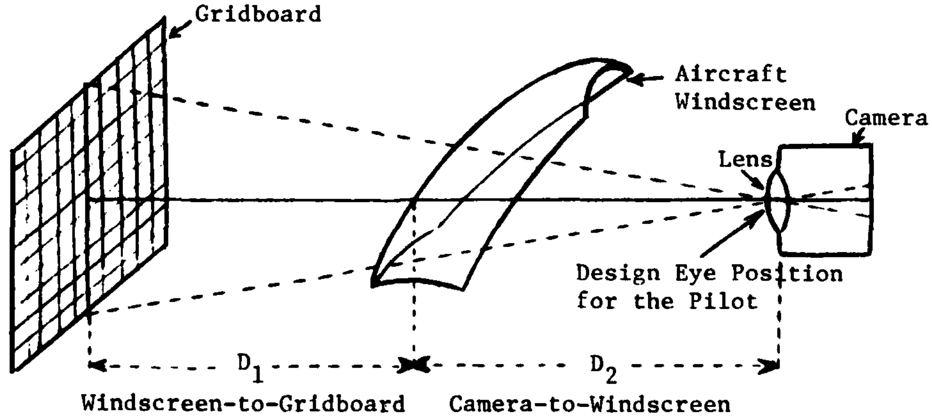


Figure 1. Photographing Geometry for Grid Line Slope Measurements.

LENSING (Thompson; 1970)

Lensing measurements are made from the same 8 by 10 inch photographic enlargements described in the preceding section. A section of the gridboard that appears in the photograph, but which was not photographed through the windscreen, is used as a baseline. The number of grid squares per inch that appear in this portion of the photograph is determined (typically 13 to 14 squares per inch). Then the number of squares in one inch sample lengths, as photographed through the windscreen, is measured for several positions in the windscreen (both in the vertical and horizontal directions). The smaller of these two numbers is divided into the larger, producing a number larger than unity. This number, when cubed to "spread the numbers out," is called the "lens factor" (Thompson; 1970).

TABLE 1

COMPARISON OF DISTANCES AND GRID BOARD SQUARE SIZES PROPOSED OR USED BY DIFFERENT ORGANIZATIONS+

Organization	Size of Squares	D_1	D_2	Units of Distortion
ASTM I	1.8 cm	450 cm	550 cm	mrad/cm
ASTM II	1.8 cm	300 cm	150 cm	mrad/cm
Douglas	1 inch	Design Eye	15 feet	Ratio: (1 in 10)
USAF/AFSC-DH-2-1				Min/inch
McDonnell Company	1 inch	3 feet	15 feet	
PPG	1 inch			Ratio
Lockheed	1 inch ½ inch			
Swedlow	1 inch			
Sierracin	1 inch			
General Dynamics	1 inch			Ratio
AFAMRL	1 inch	Design Eye	15 feet	
USAFSAM	1 inch	Design Eye		Ratio

+Refer to figure 1 for meaning of D_1 and D_2.

DISPLACEMENT GRADE (Thompson; 1970)

Displacement grade is also measured on the 8 by 10 inch gridboard photographs previously described. For the area of the windscreen to be measured, the maximum vertical displacement of any horizontal grid line is measured on the photograph in hundredths of an inch. This value is added to the maximum horizontal displacement of any vertical grid line. The sum is then multiplied by 1000 to arrive at the "displacement grade" value of the windscreen for the area measured.

COMMENTS ON LENSING AND DISPLACEMENT GRADE MEASUREMENTS

Usually, the windscreen inspectors search for and measure the maximum magnification and displacement variation areas, and do *not* "*map*" the entire windscreen. This is because windscreen procurement specifications usually specify only maximum values which must not be exceeded. The conventional measurements of lensing and displacement grade, as described above, are made from gridboard photographs. Measurement is tedious, even when only maximum distortions are measured. Many measurements must be made to find the maximums. It is not surprising that different inspectors, even using the same procedures, may differ appreciably in their measured distortion values. These measurement procedures have not produced an acceptable method of determining and quantifying distortion in aircraft windscreens. They are used despite their shortcomings, because better techniques are not available.

OPTICAL FOURIER ANALYSIS

An alternative to the windscreen optical defect measurement methods discussed above is an optical Fourier analysis technique. A short discussion of Fourier analysis for the uninitiated is given in Appendix II. The method, as applied to windscreens, was devised to simultaneously measure the defects of the whole windscreen, or at least large areas of it. The application of this method to windscreens was developed by Dr. H.L. Task (AFAMRL) who submitted it as an Air Force Invention Disclosure (Number 13,1648). A patent is now pending on his patent application filed on October 26, 1979 under the title "Measurement of Windscreen Distortion Using Optical Diffraction." In the Fourier analysis method, as used in the present report, a large (6 by 6 foot) square-wave target consisting of alternating parallel ¼ inch black and white strips is photographed with a 35 mm camera through the windscreen from the design eye position of the pilot. The resulting 35 mm slide is then optically Fourier transformed, using the laser and lens arrangement shown in figure 2. This optical transform picture is then compared to the transform of a photograph of the target pattern taken without the windscreen in place. Figure 3 and 4 show the target and its transform without windscreen (figure 3) and with a distorting windscreen (figure 4). If, as will be shown in this report, the method is valid, then the growth in spot sizes of the transformed images can be directly related to grid line slope (growth in tangential direction) and magnification (change in radial direction of position or size). The size of the optical Fourier transform photograph should increase with increase in the amount of visually perceived distortion. Measuring the size of the spots or the amount of smear of harmonics to quantify the amount of distortion in the windscreen could be done in many possible ways. For example, the area in

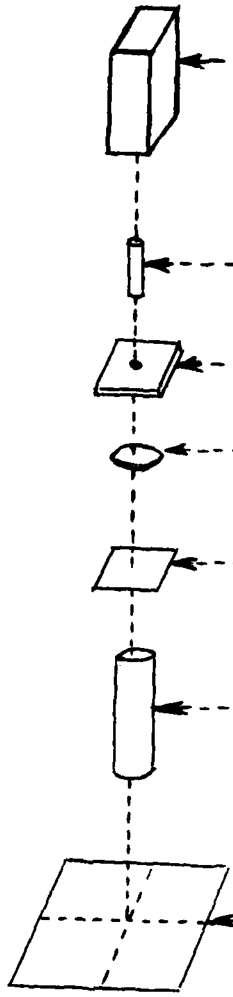


Figure 2. Optical Fourier Transform Device

the Fourier space representing a given harmonic could be scanned by a small aperture, dividing it into many small squares. The number of small squares whose energy content exceeded some preset minimum would be an objective estimate of the optical distortion of the windscreen. An objective scoring method for measuring the smear would be highly desirable. However, the equipment and technique are yet to be developed. Before the development effort is expended, it is reasonable to determine if the effort would be worthwhile. To examine this question, one determines if an optical Fourier analysis method would or could yield results in line with visual estimates of optical distortion made by examination of gridboard photographs taken through windscreens. This can be done by subjective scoring.

The scoring is based on judgments of pictures. One starts by inserting a series of windscreens, one at a time, between the camera and the gridboard, and taking a picture through each windscreen. The pictures are enlarged to make a glossy photographic print. Also, pictures are taken using a parallel line target rather than a gridboard, first with horizontal lines then with vertical lines. These pictures are placed in the Fourier apparatus and a piece of film exposed in the Fourier plane, developed and enlarged into glossy photographic prints. Observers rank the gridboard pictures according to how much distortion of the gridboard lines appear to be present. The two sets of Fourier analysis pictures are ranked according to the amount of spreading or smearing of the third harmonic "spot," yielding separate vertical and horizontal rankings. Each set of pictures is kept separate and thoroughly mixed independently and randomly for each observer so that observers do not know which Fourier picture corresponded to which gridboard picture. This procedure yields average rankings for each windscreen gridboard picture and each Fourier transform picture.

The size of the rank correlation coefficients between the gridboard ratings and the vertical and horizontal smearing ratings indicates how well the Fourier analysis technique predicts gridboard rankings. High correlations will indicate that the Fourier method can replace a gridboard picture method and that further research should be done to develop an objective method of scoring (or measuring) the amount of spreading of the second harmonic or some combination of harmonics.

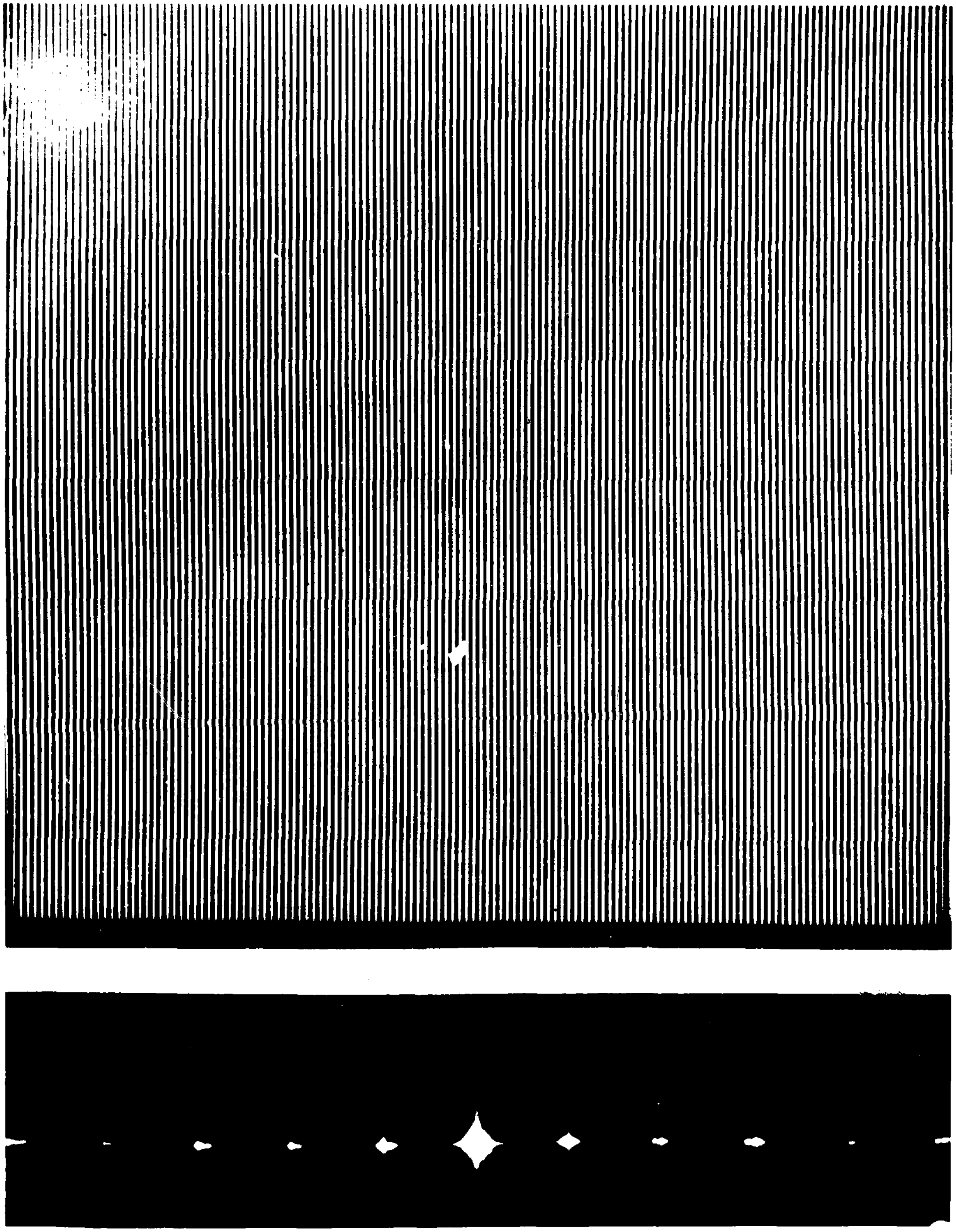


Figure 3. Photograph of Vertical Line Target With No Intervening Transparency (top) and Fourier Transform of the Photograph (bottom).

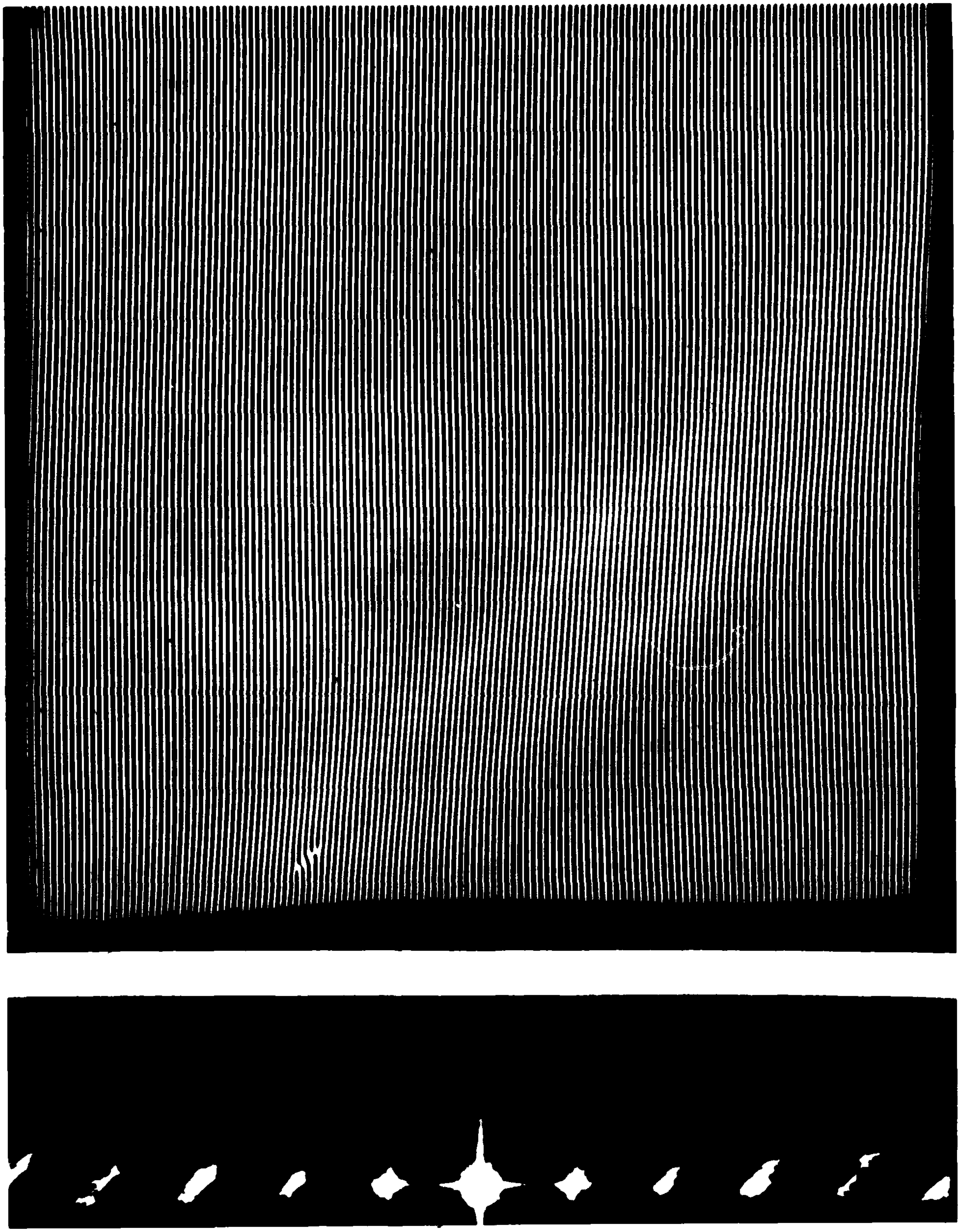


Figure 4. Photograph of Vertical Line Target with A High Distortion Transparent Panel (no. 11) Intervening Between Camera and Target. At the Bottom is the Fourier Transform of the Photograph.

EXPERIMENT 1

METHOD: EXPERIMENT 1

At the time the data were collected a set of windscreens was not available. Instead of real windscreens, a set of 11 flat Plexiglas® panels that had been fabricated to contain optical distortions ranging from very little to considerable was used. Keep in mind that the range of distortion used influences the data, and that a smaller range would lead to lower correlations than were obtained.

Glossy 8 by 10 inch photographic enlargements were made from a 35 mm negative taken of a gridboard through each of the eleven panels. The set-up for taking the pictures is shown in figure 1. The panels were sloped at an angle of 49° to the camera's line of sight. Figures 5 and 6 are gridboards photographed through low and high distortion panels, respectively. Two sets of 35 mm negatives were also taken through each distortion panel of squarewave, i.e., parellel stripe, targets. One set was taken with a vertical line target with each distortion panel and one with a horizontal line target. The two sets of square-wave target pictures were used as the input to the optical Fourier analysis device shown in figure 2. A 35 mm photographic film was exposed in the Fourier transform plane by illuminating the photographic negative with an argon laser. Glossy 8 by 10 inch photographic enlargements were made from the developed film. Figures 7 and 8 are Fourier pictures made through the same distortion panels used in taking the gridboard pictures of figures 5 and 6.

The grid photographs were "shuffled" like a deck of cards each time before being handed to test subjects to obtain a random order or presentation. The instruction sheet said: "Arrange these pictures from the one that has the least distortion to the one that has the most." The task of arranging the Fourier vertical line target photographs from the one with the most compact third harmonic to the one with the least compact or most spread or smeared third harmonic was similarly done with a "deck" of 11 pictures that were also randomly shuffled for each rater or subject. The instructions were: "Arrange these pictures from best to worst, best meaning having the smallest or most tightly packed third harmonic. The third harmonic is the third light patch out from the central dot. Use the patch marked with an arrow in making judgments." There were two sets of 11 Fourier pictures, one for vertical frequencies which was made using vertical lines. Each set of pictures was ranked separately. No questions were answered nor hints given by the test administrator on how to rank any one of the three sets of pictures. Test subjects had only the instruction to go by. Twenty-three raters ranked the grid pictures and the Fourier pictures.

RESULTS: EXPERIMENT 1

Table 2 lists the ranking data for 23 raters or test subjects for the 11 transparent distortion panels. The ranks are summed in the "Sum" column, for all 23 raters for each panel, and the sums of ranks are then ranked. This yields an overall ranking, or ranking over all observers, for each panel. This overall ranking is listed in the column labeled "Rank" at the left of the table. The ranks for the horizontal and the vertical Fourier are averaged to obtain a Fourier or "F" in the table. The overall rank of each distortion panel for the gridboard (G), the horizontal (H) and vertical (V) Fourier ranks and the Fourier [F or ½ (H + V)] are listed in the column labeled "Rank" at the left of the table. The overall rankings are also listed vertically by type in table 3, to simplify comparisons. The optical distortion ranks of the gridboards are plotted against the horizontal and the vertical Fourier compactness ranks, respectively, in the scatter plots or diagrams of Figure 9.

The scatter plots in Figure 9 clearly show that the two sets of data are closely related. A high, medium or low rating of a panel on a grid photograph goes with a high, medium, or low rating, respectively, on the corresponding vertical or horizontal Fourier picture. From the table it appears that Fourier picture compactness ranks are fairly efficient predictors of the optical distortion ranks of the gridboard pictures. The relationship apparent from examination of tables 2 and 3 are verified in table 4, which lists some correlations between sets of ranks.

From table 5, note that the rank correlation coefficient, r', between Fourier compactness rank for the horizontal Fourier pictures (H) and the gridboard optical distortion rank (G) is .6818. For the vertical Fourier pictures the r' is .8818. Both of these values are statistically significant ($P < .01$). It is concluded from this that the obtained correlations are not attributable to chance: the relationships between G and H and between G and V are real and appreciable in size. The Fourier pictures can be used to predict optical distortion. The vertical Fourier ranks are more efficient predictors of optical distortion than are the horizontal ranks.

The ranks on the horizontal and vertical Fourier judgements of a transparancy can differ appreciably, as is the case with distortion Panel 8. How closely are horizontal and vertical Fourier compactness rankings related? The rank correlation coefficient, r', between the two sets of ranks for the 11 distortion panels is +.5818. For a sample size of 11 panels this is not statistically significant at the .05 level of significance. If Panel 8 is omitted, r' goes up to +.7697. However, one must conclude that the data for all 11 distortion panels indicate that the horizontal and vertical Fourier compactness rankings are independent: neither is predictable from the other.

It was found that G and V were significantly related and, if Panel 8 were to be omitted, G and H were also significantly related. It might be worthwhile to use both horizontal and veritical Fourier ranks for predicting G. In table 1 the numbers in the "F" row are the averages of H and V, i.e.,

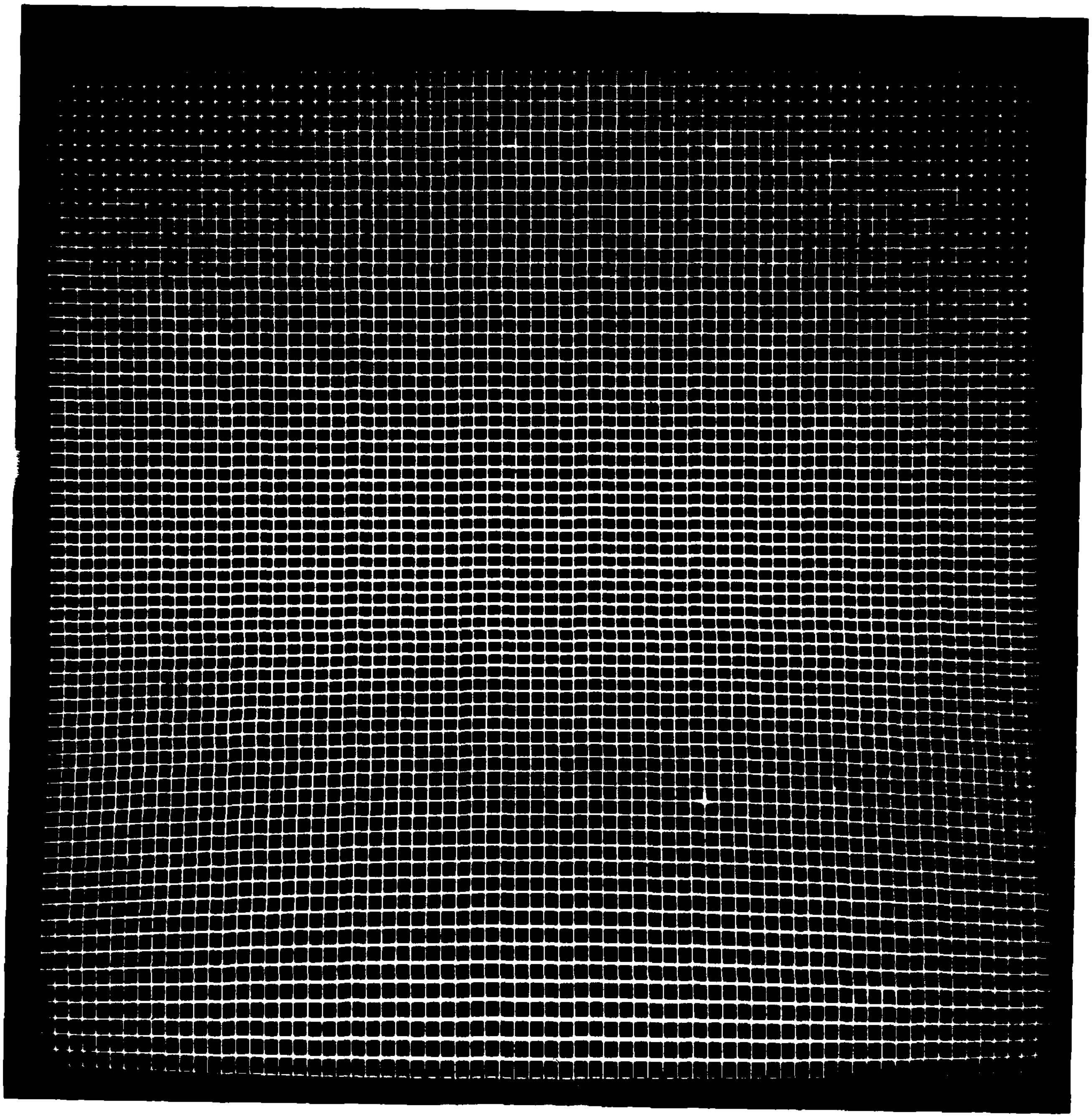


Figure 5. Gridboard Photograph Taken Through a Low Distortion Transparent Panel, Panel 8.

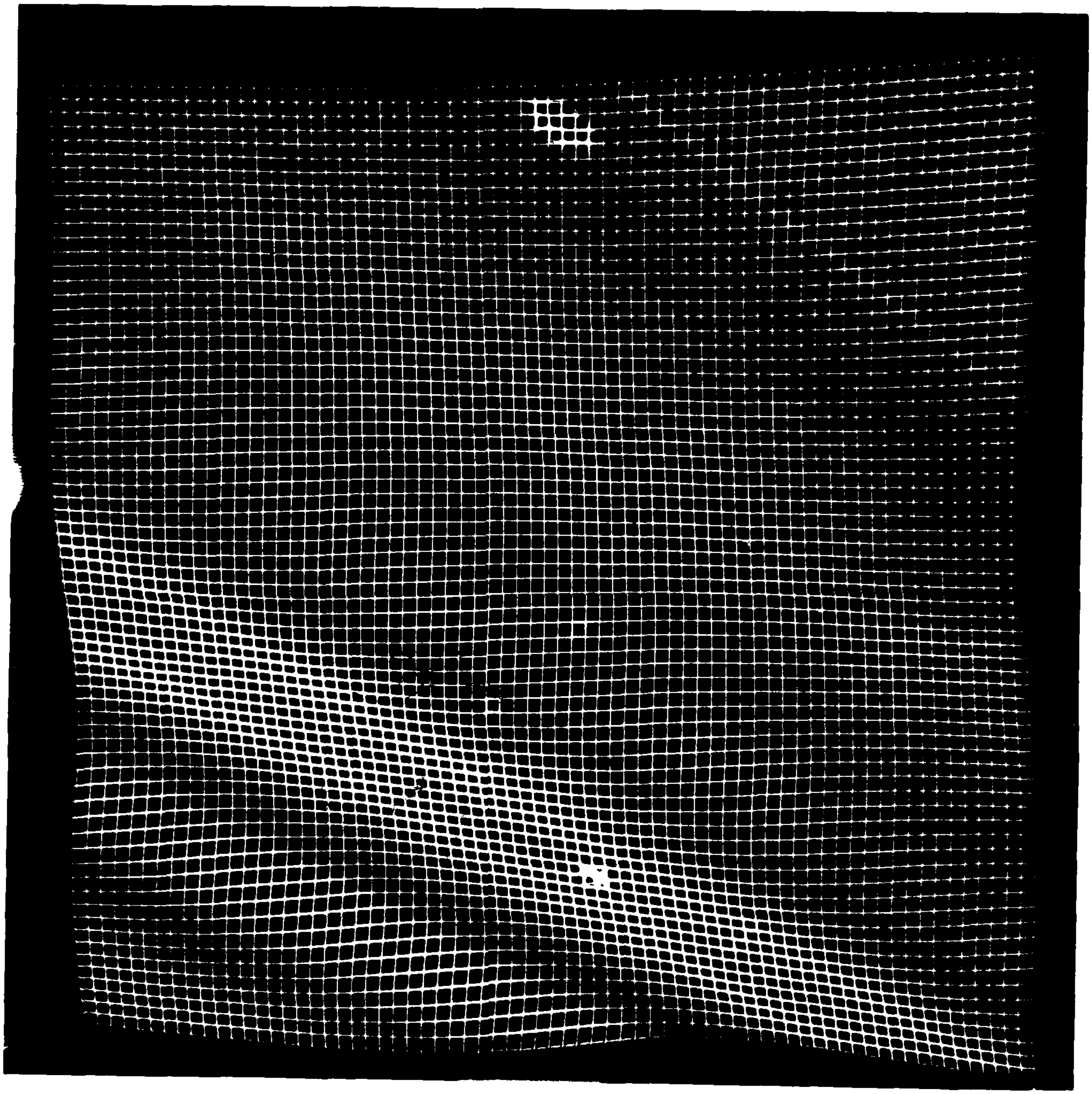
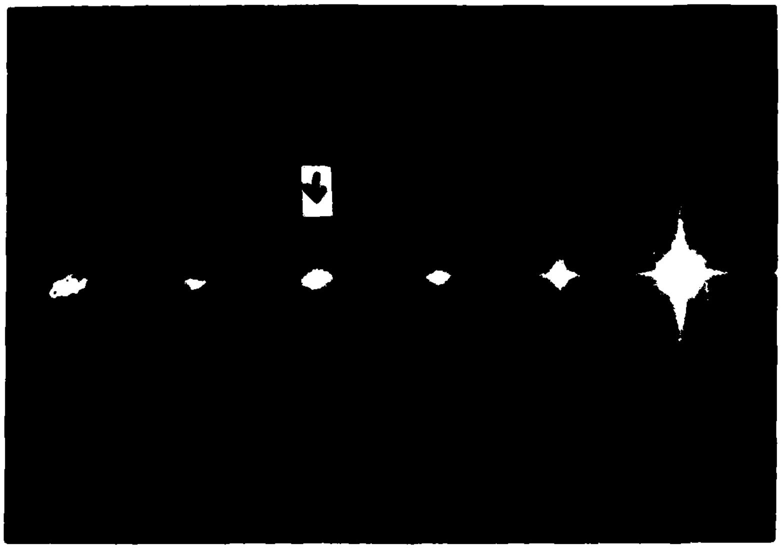
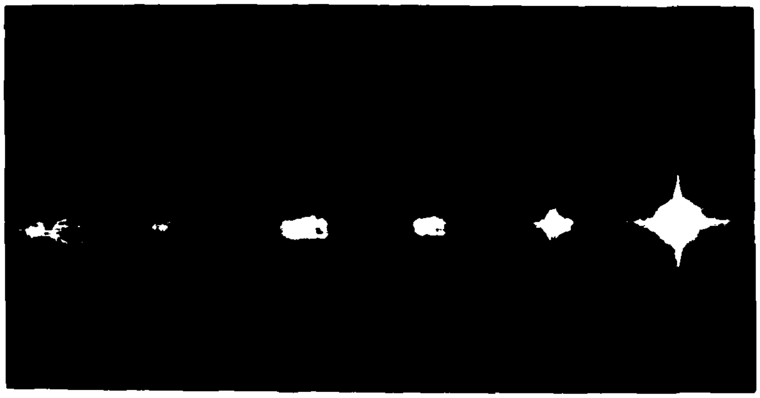


Figure 6. Gridboard Photograph Taken Through a High Distortion Transparent Panel, Panel 11.

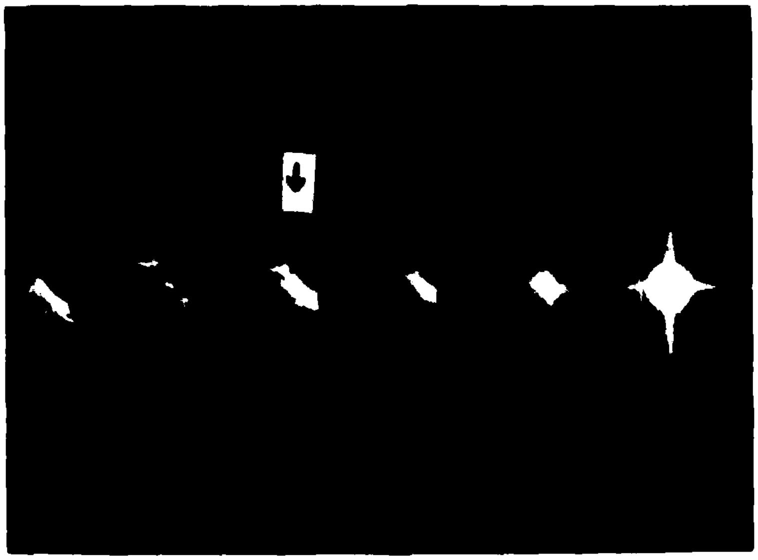


(A) Vertical Fourier Using A Horizontal Line Target



(B) Horizontal Fourier Using a Vertical Line Target

Figure 7. Fourier pictures using the same low distortion transparent panel used in making the picture shown in Figure 5. Only the central component and harmonics on one side of it are shown.



(A) Vertical Fourier Using A Horizontal Line Target

(B) Horizontal Fourier Using a Vertical Line Target

Figure 8. Fourier pictures using the same high distortion transparent panel used in making the picture shown in Figure 6. Only the central component and harmonics on one side of it are shown.

TABLE 2

RANKINGS OF GRIDBOARD PHOTOGRAPHS FOR DISTORTION AND RANKINGS OF FOURIER PHOTOGRAPHS FOR COMPACTNESS OF THE THIRD HARMONIC

		RATER OR TEST SUBJECT																										
PANEL		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	SUM	RANK	MEDIAN	MODE
1	G*	1	3	2	3	4	4	1	4	6	4	2	3	6	2	5	3	2	2	6	5	2	4	1	75	3	3	2
	H	3	6	6	4	5	5	4	6	5	3	5	5	7	6	5	7	6	5	6	5	4	4	2	114	5	5	5
	V	1	1	3	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	4	30	1	1	1
	F	1.5	4	5	1	1.5	2.5	2	3.5	2	2	2.5	2	4	3.5	2	4	2.5	3	3.5	2.5	1	1.5	2.5	59.5	2	2.5	2.25
2	G	5	2	4	5	1	5	2	8	5	8	6	5	7	3	4	2	3	3	5	6	5	7	7	108	5	5	5
	H	4	4	4	5	4	4	5	5	4	1	4	6	4	4	4	4	5	4	4	4	6	5	1	95	4	4	4
	V	2	2	4	2	2	2	2	5	2	2	2	2	2	2	4	2	2	2	2	2	2	2	3	54	2	2	2
	F	3	2.5	4	4	1.5	2.5	3.5	5.5	2	1	2.5	3.5	2	1.5	4	1.5	2.5	3	1	2.5	4	3	1	61.5	3	2.5	4
3	G	8	7	7	7	8	8	8	8	7	7	8	8	3	7	7	7	8	8	7	8	8	6	3	163	8	7	8
	H	6	8	7	6	7	7	8	7	8	8	9	4	6	7	8	5	3	8	5	7	5	8	8	155	7	7	8
	V	8	8	8	8	8	8	8	8	8	7	8	8	8	9	8	8	8	8	10	9	8	8	8	187	8	8	8
	F	8	8	8	8	8	8	8	8	8.5	7.5	9	7	8	8.5	8.5	7.5	8	8.5	8	8	7.5	8.5	8.5	185.5	8	8	8
4	G	9	10	9	9	9	10	10	9	10	10	9	10	8	11	9	10	10	10	10	9	9	9	10	219	10	10	10
	H	10	10	10	10	11	10	11	10	11	10	10	10	10	10	11	11	10	10	10	10	11	10	10	236	10	10	10
	V	10	9	10	10	10	10	9	10	10	11	10	9	10	10	10	10	11	10	9	10	10	10	10	228	10	10	10
	F	10	9.5	10	10	10.5	10	10.5	10	10.5	10.5	10	9.5	10	10	10.5	10.5	10.5	10	10	10	10.5	10	10	233	10	10	10
5	G	10	9	10	10	10	9	9	10	9	9	10	7	10	9	10	9	9	9	9	10	11	10	9	217	9	9	9
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8	G	4	1	3	2	3	3	2	2	2	6	3	2	5	6	2	1	1	1	2	3	3	2	4	63	2	2	2
	H	9	5	5	9	9	9	9	9	9	4	8	7	9	9	9	9	9	9	9	8	9	9	9	190	9	9	9
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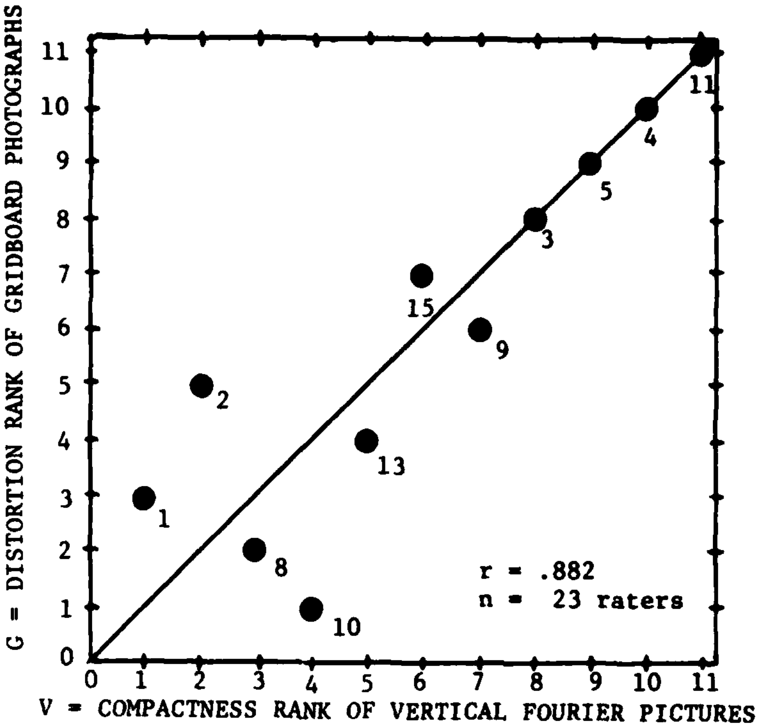
	F	7	5.5	2	6.5	7	6.5	6.5	5.5	6	4	6	5.5	7	7	6	7.5	8	7	6	6	7.5	6.5	5	141.5	6	6.5	6
9	G	6	6	8	6	6	7	3	5	3	3	7	4	9	4	8	6	6	6	3	4	8	8	8	132	6	6	6
	H	2	3	3	2	2	3	2	3	2	6	3	3	3	2	3	2	2	3	1	3	3	2	5	63	3	3	3
	V	7	6	7	7	7	7	6	6	6	6	5	7	7	7	6	7	7	7	6	7	7	7	6	150	7	7	7
	F	4	5.5	6	5	5	5	3.5	3.5	5	5	2.5	5.5	5.5	5	5	5	5	5	3.5	5	5.5	5	6	111	5	5	5
10	G	3	4	1	1	2	1	6	1	1	1	1	1	1	1	1	4	4	4	1	1	1	1	2	44	1	1	1
	H	1	1	2	1	1	1	1	2	1	6	2	1	2	1	1	1	1	1	3	1	1	1	4	38	1	1	1
	V	3	5	2	5	3	4	3	2	5	5	3	4	3	5	3	6	3	5	4	4	6	4	2	89	4	4	3
	F	1.5	2.5	1	2.5	1	1	1	1	2	6	1	1	1	1.5	1	3	1	3	3.5	1	2.5	1.5	2.5	43	1	1.5	1
11	G	11	11	11	11	11	11	11	11	11	11	11	11	11	10	11	11	11	11	11	11	10	11	11	251	11	11	11
	H	11	11	11	11	10	11	10	11	10	11	11	11	11	11	10	10	11	11	11	11	10	11	11	247	11	11	11
	V	11	11	11	11	11	11	10	11	11	10	11	11	11	11	11	11	10	11	8	11	11	11	11	247	11	11	11
	F	11	11	11	11	10.5	11	10.5	11	10.5	10.5	11	11	11	11	10.5	10.5	10.5	11	10	11	10.5	11	11	248	11	11	11
13	G	2	5	5	4	6	2	4	7	4	5	4	2	2	5	3	5	5	6	4	2	4	3	6	97	4	4	5
	H	5	2	1	3	3	2	3	1	3	2	1	1	1	3	2	3	4	2	2	2	2	3	3	55	2	2	2
	V	6	3	6	3	4	5	6	4	4	4	7	6	6	4	5	3	4	3	5	5	5	5	5	108	5	5	5
	F	5	1	3	2.5	4	4	5	2	4	3	2.5	3	3	3.5	3	1.5	4	1	3.5	4	2.5	4	4	73.5	4	3.5	4
15	G	7	8	6	8	7	6	7	3	8	2	5	4	4	8	6	8	7	7	8	7	7	5	5	148	7	7	7
	H	7	7	8	7	6	6	6	4	6	7	7	5	5	5	6	6	7	6	7	6	7	6	6	146	6	6	6
	V	5	7	5	6	6	6	7	7	7	8	6	5	5	6	7	5	6	6	7	6	3	6	7	139	6	6	6
	F	6	7	7	6.5	6	6.5	6.5	7	7	7.5	7	5.5	5.5	6	7	6	7	6	7	7	5.5	6.5	7	152.5	7	7	7

* KEY: G - GRIDBOARD PHOTOGRAPH; H - HORIZONTAL FOURIER PICTURE; V - VERTICAL FOURIER PICTURE; F - RANK ON SUM OF H AND V.



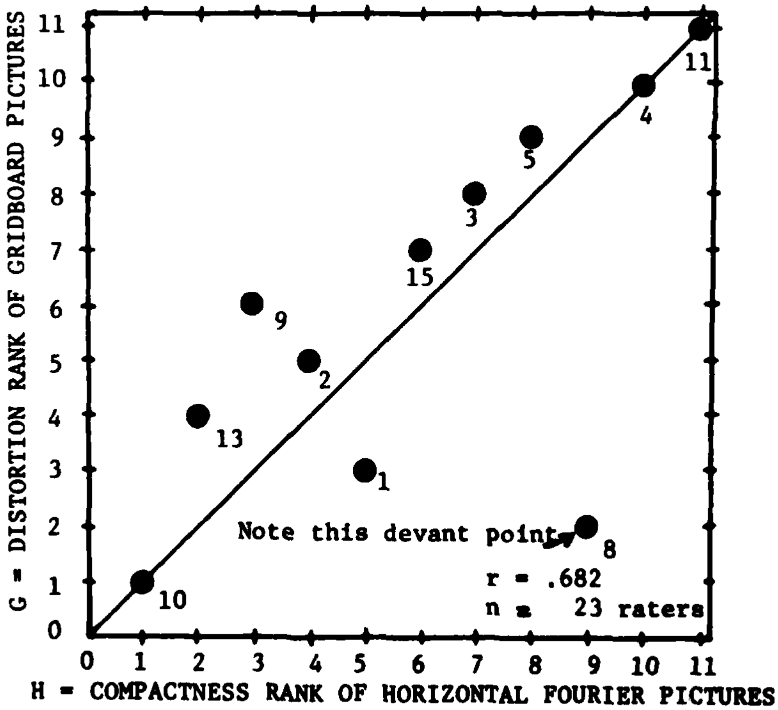


Figure 9. Plots of gridboard distortion ratings against compactness rankings of the horizontal and vertical Fourier third harmonic pictures.

TABLE 3

RANKS OF GRIDBOARD AND FOURIER PHOTOGRAPHS

		Ranks of Pictures										
	Panel:	1	2	3	4	5	8	9	10	11	13	15
G	Gridboard Photograph	3	5	8	10	9	2	6	1	11	4	7
H	Horizontal	5	4	7	10	8	9	3	1	11	2	6
V	Vertical	1	2	8	10	9	3	7	4	11	5	6
F	Fourier	2	3	8	10	9	6	5	1	11	4	7

TABLE 4

CORRELATIONS BETWEEN SETS* OF RANKINGS MADE BY 23 RATERS

CORRELATED DATA SETS		RANK CORRELATION COEFFICIENT: ALL PANELS	RANK CORRELATION COEFFICIENT: No. 8 OMITTED +
H-V	(Horiz. Fourier)(Vert. Fourier)	.5815	.7697
G-H	(Grid Photo)(Horiz. Fourier)	.6818	.9152
G-V	(Grid Photo)(Vert. Fourier)	.8818	.9273
G-F	(Grid Photo)(Overall** Fourier	.9000	.9879
G-F'	(Grid Photo)(Optimal Fourier + +	.9894	.9791

* Each data set consists of the rank of each picture as established by 23 observers. The data sets are given in the rank column of table 1.

** Overall Fourier is the rank of each picture as determined by the sums of the ranks of all 23 raters on both horizontal and vertical Fourier pictures. This composite rank is not the average of the horizontal and vertical rank columns at the right of the table.

\+ The "sums" of Table 1 are ranked without including the sum for panel 8.

\+ + Optimal Fourier is the least-squares "best" linear combination of the H and V ranks, "best" in that it maximizes the F-G correlation.

$F = (H + V)/2$. The r' between the average Fourier rank, F, and the gridboard photograph distortion rank, G, is .9000, which is large and statistically significant ($P < .01$). However, the r' between G and V alone was .8818, so that the gain in r' by using both the horizontal and vertical Fourier is negligible. Note, however, that if Panel 8 is omitted, the r' goes up to +.9879, which is a very large correlation coefficient.

Since, for all 11 panels, the vertical ranks correlated higher than the horizontal ranks with gridboard distortion ranks, one would expect that, in a Fourier composite rank, the weighting of the vertical ranks should exceed that of the horizontal ranks. When simply averaged, as in the previous paragraph, weightings were equal. Let the maximum Fourier-gridboard picture correlation achievable by a linear weighting of H and V be given by the equation $F = AH + BV$. It can be shown, by a least squares statistical technique, that the equation is $F = .2598H + .7381V$. Note that $B/A = 2.8$, so that the optimum weighting, B, of the vertical Fourier ranks in the optimum composite Fourier rank is almost three times that of the horizontal rank weight, A. When the optimum composite F values given by the formula are used for all 11 distortion panels, the Fourier-gridboard distortion (F-G) rank correlation coefficient is a surprising .9894. This is an appreciable gain over the .9000 given by simply averaging the

Fourier ranks to predict the gridboard optical distortion ranks. A correlation coefficient, r', of .9894 is extremely high. It is so high that one could hardly expect an increase by omitting the data for Panel 8. When Panel 8 is omitted and the sums of ranks are reranked, the new optimum weighting formula becomes F = .4777H + .5303V, with H and V having similar "weightings." The r' between weighted Fourier compactness rank and gridboard optical distortion rank with Panel 8 omitted is .9791, a sight loss in r' value from using all 11 distortion panels, but nontheless, still a very high correlation. Clearly, weighting V and H differently in a composite results in a significant and important gain in accuracy as compared to an equal weight (averaging) composite or to use of the vertical Fourier alone.

As a matter of interest, note on the bottom scatter plot of figure 9 that optical distortion Panel 8 is a deviant point. It is located some distance away from the equal ranks straight line shown in the figure. Distortion Panel 8 was ranked high on horizontal Fourier compactness and low on vertical Fourier compactness. Panel 8 had the largest H-V difference of any of the 11 panels. Both H and V are related to gridboard photograph distortion rank. Since 8 was a deviant point, the exclusion of Panel 8 data resulted in an appreciable increase in the size of the G-H correlation coefficient. If the sums of the ranks of table 1 are ranked without using the data for distortion Panel 8, the value of r' increases from .6818 to .9152. The scatter plot of the reranked data is shown in figure 10.

It is apparent that an occasional panel or windscreen will be found whose optical distortion is not predictable with any useful accuracy from its horizontal Fourier picture. One can only conjecture that occurrence of an occasional panel which may be much more distorting in the horizontal than in the vertical direction, or vice versa, is to be expected. As a further point of interest, it has been found in the past, by aircraft windscreen manufacturers, that an occasional windscreen that failed to meet Air Force contractual requirements for magnification and optical deviation was judged by windscreen inspectors and by aircraft pilots as appearing to be optically satisfactory. In these cases it appears that slow changes over a windscreen surface, in magnification and in deviation, may be judged as satisfactory even if the two values become appreciable in magnitude.

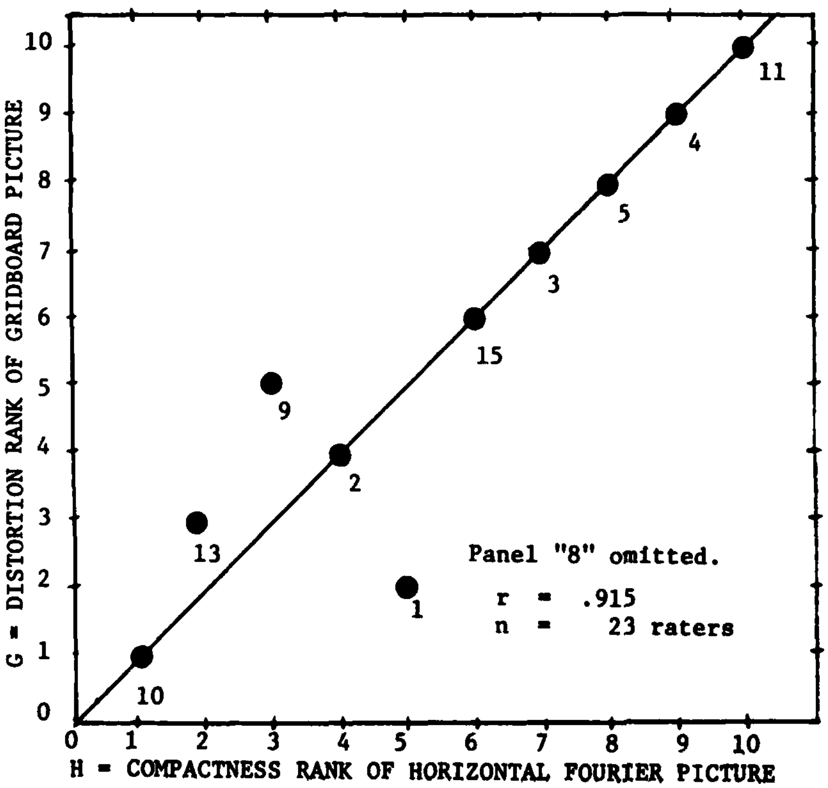


Figure 10. Distortion ranks of gridboard photographs plotted against compactness ranks of horizontal Fourier pictures with picture "8" omitted.

In previous paragraphs concern has focused on correlations between averages over all raters. Some r' values for the 23 individual raters are listed in table 5. The "Max r' " column to the right of the table lists the largest r' values for the rater in the row. The following points may be noted from examination of the table:

- Of the 23 "Max r'" values, 13 are for G-V correlations and 10 are G-F.
- *Only 1 maximum value is in the H-V column. It is for rater 10. He has the largest r' value in the H-V column, but also the lowest r' value in the G-F column.*
- For 18 of the 23 raters the G-V correlation exceeded the G-H correlation. Thus, for 78% of the raters their gridboard photograph distortion ranking (G) was predicted (or measured) more efficiently by their vertical Fourier rank (V) than by their horizontal Fourier rank (H).
- *The largest r' in the entire table was in the G-V column: a .945 for rater 3.*

TABLE 5

RANK CORRELATION COEFFICIENTS BETWEEN DISTORTION RANK OF GRID PHOTOGRAPHS AND COMPACTNESS RANK FOR FOURIER PICTURES

RATER	(HORIZONTAL)-(VERTICAL)	(GRID PHOTO)-(HORIZONTAL)	(GRID PHOTO)-(VERTICAL)	(GRID PHOTO)-(FOURIER)	
	$r'_{H\text{-}V}$	$r'_{G\text{-}H}$	$r'_{G\text{-}V}$	$r'_{G\text{-}F}$	MAX r'
1	+.673	+.691	+.855	+.857	G-F
2	+.736	+.736	+.900	+.807	G-V
3	+.655	+.691	+.945	+.900	G-V
4	+.591	+.664	+.809	+.832	G-F
5	+.682	+.645	+.909	+.864	G-V
6	+.582	+.745	+.836	+.868	G-F
7	+.609	+.582	+.836	+.770	G-V
8	+.536	+.536	+.855	+.736	G-V
9	+.564	+.709	+.718	+.773	G-F
10	+.936	+.527	+.464	+.450	H-V
11	+.600	+.609	+.827	+.809	G-V
12	+.518	+.691	+.736	+.834	G-F
13	+.491	+.627	+.518	+.643	G-F
14	+.491	+.791	+.782	+.920	G-F
15	+.577	+.591	+.855	+.809	G-V
16	+.418	+.436	+.855	+.716	G-V
17	+.509	+.382	+.891	+.705	G-V
18	+.627	+.518	+.918	+.789	G-V
19	+.426	+.691	+.645	+.777	G-F
20	+.618	+.845	+.700	+.843	G-F
21	+.418	+.655	+.727	+.836	G-F
22	+.709	+.527	+.745	+.707	G-V
23	+.609	+.482	+.691	+.627	G-V
MEDIAN	.591	.645	.827	.807	G-V
MEAN**	.611	.645	.810	.794	

* Fourier, here, is the rank of the sums of ranks for the horizontal and vertical fourier pictures. It is not the average of the horizontal and vertical ranks.

** The proper mean of a group of correlation coefficients is not the arithmetic mean, but is calculated, here, by taking the inverse hyperbolic tangent of each r' in the column, summing all 23, dividing by 23 and taking the hyperbolic tangent of this quantity. Note that the values are very close to the medians.

- As expected, the mean and median values at the bottom of the table show that the vertical Fourier is better than the horizontal for predicting the distortion rank of a gridboard photograph.

- Also, the G-V mean of .810 was, for all practical purposes, the same as the G-F mean of .794, while the G-V median of .827 exceeded the .807 G-F median.

The individual rater correlations, as expected, support the findings from the group averages:

- Fourier compactness can be used to measure optical distortion.

- The vertical Fourier compactness values are more efficient for predicting or measuring optical distortion than are the horizontal Fourier values.

- A simple average (or equal weight composite) of V and H was no more efficient than the vertical values alone. An unequal weight composite Fourier is required.

EXPERIMENT 2

In the first experiment, the authors of this study as well as the picture raters noted that some of the pictures were very similar to others in amount of distortion or in amount of compactness of the third harmonic. Such pictures were not easily ranked in the series. In other words, the spacing of each quantity being ranked was not uniform. In making only the ordering or sequencing judgments required to rank pictures, as was done in Experiment 1, no spacing information is obtained. It might be conjectured that, had estimates of magnitude, rather than only ranks, been obtained, correlations between quantities would increase. A second experiment was done to examine this possibility.

An experimental method that yields measurement rather than ordering or ranking was desired. The method of magnitude estimation, although it is subjective, is such a method. In this method the rater compares each test picture to a standard picture and assigns a number to the test picture. The standard picture in the present study was assigned a value of 5 on a scale ranging from 1 to 10. On the scale, 1 represented a perfect picture. The instructions to the raters in Experiment 2 were typed and were handed to the raters to study before taking data. The instructions are given in Appendix I of this report. Ten raters, working independently, first ranked the 11 grid photographs from best or least optical distortion to worst or most distortion. They then estimated the magnitude of the optical distortion of each picture as compared to the one that, after ranking was completed, was labeled by the test administrator as a "5."

In a similar manner, they first ranked, then estimated the magnitude of the compactness of the third harmonic of the horizontal Fourier pictures. They then ranked and magnitude estimated the vertical Fourier pictures. The picture that had a 5 label attached to it was the photograph taken through distortion panel 3 for both the gridboard pictures and the horizontal Fourier pictures. For the vertical Fourier pictures, the standard was the one taken through distortion panel 13. These particular pictures appeared to the test administrator to be at approximately 5 on an estimation scale ranging from 1 to 10. Only after each observer ranked all of the pictures was he informed which picture was the standard or "5" picture so that he could then do the magnitude estimation task.

RESULTS: EXPERIMENT 2

The data from the second experiment are presented in tables 6, 7 and 8. Note the small variability between raters, as evidenced by the table entries and by the column of standard deviations (S.D.'s) in each table. This rather small scatter or variability is found for both the ranking data and the magnitude estimation data. The majority of all judgments of a given type on a particular distortion panel appear to be in rather close agreement.

The first question that may occur to the reader is "How closely do the rankings and the magnitude estimations agree?" Keep in mind that the pictures were first ranked, then the magnitude of the quantity of interest, relative to the standard, was estimated. The estimates took place with the pictures still in the order in which they were ranked by the rater. This procedure made the rankings and the magnitude estimates agree in rank and increased the correlation between rankings and estimations. Thus, the data do not reveal how closely the ranks and magnitude estimates would agree if the estimates had been made with unranked or randomly arranged pictures. Table 9 gives the correlation coefficients for the ranking and magnitude estimation data of individual observers. From the table it may be noted that the correlations are quite high. The mediums at the bottom of the table indicate that the ratings of most individuals are in good agreement. As expected, there is excellent agreement between rankings and magnitude estimates. Note also the generally higer r' values in the vertical Fourier column as compared to the horizontal Fourier column. Nine of the 10 vertical values exceed the horizontal ones, and the median vertical r' is .876 as compared to .790 for the horizontal.

The relationship between magnitude estimates for the three sets of pictures are given for individual observers in table 10. In all three columns the correlation coefficients are quite high. Compare the size of the medians at the bottom of the table. They indicate that the "compactness" estimates for both the vertical and the horizontal Fourier pictures are highly correlated with the distortion estimates made of the gridboard photographs. The data also show that the horizontal and vertical estimates are almost as closely correlated with each other (.771) as either one is correlated with the gridboard distortion estimates. The medians at the bottoms of the first two columns of table 10 are essentially equal: .810 versus .790. For individual observers, the horizontal and vertical harmonic compactness estimates appear to be essentially equal in the efficiency with which they predict optical distortion estimates. Later in this report it is shown that this equivalence does not hold for the averages of groups of individuals.

In tables 4, 5 and 6, for each distortion panel or windscreen, there is an average value across all 10 raters. These sets of averages can be used to calculate correlation coefficients whose magnitudes will enable one to compare the magnitude estimation method with the ranking method for efficiency in predicting judged optical distortion. These correlations between averages for the distortion panels are given in table 11. Note the very high statistically significant ($P < .01$) correlation of .9773 between the rankings and the magnitude estimations of the optical distortion of the gridboard photographs. The reason for such a high correlation is due, in part, to the already mentioned experimental procedure where estimates where made while the pictures were in the order in which they were ranked by the person making the estimation.

TABLE 6

DISTORTION OF GRIDBOARD PHOTOGRAPHS

(A) RANKING

Panel	Rater or Test Subject											Average S.D. = 1.31		
	24	25	26	27	28	29	30	31	32	33	Mean	MDN	Mode	S. D.
1	4	1	1	6	8	2	1	2	4	4	3.30	3.00	3**	2.36
2	1	4	5	3	1	3	2	4	3	6	3.20	3.17	3	1.62
3	8	8	6	8	6	8	8	7	8	8	7.50	7.79	8	.85
4	10	10	10	10	9	10	11	9	9	11	9.90	9.90	10	.74
5	9	9	9	9	10	9	9	10	10	9	9.30	9.21	9	.48
8	5	3	2	5	2	1	4	3	1	3	2.90	2.83	3	1.45
9	7	5	7	4	5	5	5	5	6	2	5.10	5.10	5	1.45
10	2	2	3	1	3	4	3	1	2	1	2.20	2.17	2**	1.03
11	11	11	11	11	11	11	10	11	11	10	10.80	10.88	11	.42
13	6	6	4	2	4	6	6	6	5	5	5.00	5.50	6	1.33
15	3	7	8	7	7	7	7	8	7	7	6.80	7.07	7	1.40

(B) MAGNITUDE ESTIMATION

Panel	Rater or Test Subject											Average S.D. = .92		
	24	25	26	27	28	29	30	31	32	33	Mean +	MDN	Mode	S. D.
1	3.4	2.5	1.	4.0	5.9	1.6	1.5	2.5	2.0	2.3	2.45	2.50	2.5	1.40
2	2.5	3.2	4.2	2.0	2.0	2.0	2.0	3.2	1.8	3.7	1.55	1.15	2	.86
3	8.1	8	8.4	7.5	6.4	6.2	7.2	6.0	6.0	8.8	2.55	2.25	6	1.06
4	6.2	6.5	8.0	7.0	7.5	6.0	6.0	8.0	7.5	7.0	6.93	7.00	7.25*	.77
5	3.6	3	2.0	3.8	2.6	1.5	4.1	3.0	1.5	3.2	2.68	3.00	2.25*	.92
8	4.7	3.7	5.3	3.9	4.6	3.5	4.2	3.8	3.0	3.0	3.87	3.75	3 25*	.76
9	2.7	2.7	3.0	1.5	2.8	2.8	4.0	2.0	1.6	2.8	2.49	2.75	2.8	.73
10	9.2	8.2	9.5	9.0	8.9	7.3	7.0	9.0	8.0	8.5	8.42	8.70	9	.83
11	4.1	3.5	3.8	1.8	4.0	4.0	4.3	4.0	2.5	3.5	3.45	3.90	4	.80
15	3.2	4	7.0	4.5	5.2	4.5	4.5	5.0	3.5	4.0	4.48	4.50	4.5	1.10

+ For magnitude estimation the geometric mean is used.
* When dual modes occur, the value given is midway between the two groupings.
** *When no mode is present, the value is the median.*

NOTE: Panel 13 was the standard, hence it is not in table (B).

TABLE 7

COMPACTNESS OF HORIZONTAL FOURIER THIRD HARMONIC

(A) RANKING

Panel	Rater or Test Subject											Average S.D. = 1.5		
	24	25	26	27	28	29	30	31	32	33	Mean	MDN	Mode	S. D.
1	5	5	5	2	5	4	6	2	5	5	4.40	5.83	5	1.35
2	4	4	3	5	4	5	3	3	4	4	3.90	3.90	4	.74
3	6	6	6	8	7	7	1	7	6	7	6.10	6.50	6.5**	1.91
4	11	10	10	11	11	10	10	9	10	11	10.30	10.30	10	.67
5	8	8	9	9	8	8	7	8	8	9	8.20	8.17	8	.63
8	9	9	7	4	6	9	9	11	9	6	7.90	8.70	9	2.08
9	2	1	4	6	1	2	5	5	3	3	3.20	3.00	2*	1.75
10	1	2	2	3	2	1	4	1	1	1	1.80	1.50	1	1.03
11	10	11	11	10	10	11	11	10	11	10	10.50	10.50	10.5	.53
13	3	3	1	1	3	3	2	4	2	2	2.40	2.50	3	.97
15	7	7	8	7	9	6	8	6	7	8	7.30	7.25	7	.95

(B) MAGNITUDE ESTIMATION

Panel	Rater or Test Subject											Average S.D. = 1.02		
	24	25	26	27	28	29	30	31	32	33	Mean +	MDN	Mode	S. D.
1	4.7	4.0	4.2	3.0	4.5	3.5	6.5	2.5	4.5	4.4	4.05	4.30	4.5	1.09
2	4.5	3.6	3.0	3.8	4.0	4.5	5.2	3.0	4.2	4.2	3.95	4.10	4.10**	.68
4	9.2	7.0	8.0	6.5	8.5	6.4	9.0	6.0	8.0	6.8	7.46	7.50	8	1.15
5	5.8	6.0	7.1	5.5	5.5	5.3	7.0	5.3	6.5	5.7	5.94	5.75	5.40*	.67
8	7.0	6.3	6.2	3.7	4.7	6.0	8.0	9.0	7.5	4.8	6.12	6.25	6.25	1.63
9	3.5	3.0	3.2	4.0	3.0	2.8	6.0	4.0	3.5	3.9	3.60	3.50	3.5	.92
10	3.0	3.3	2.2	3.5	3.2	2.3	5.3	2.0	2.5	3.5	2.96	3.10	3.5	.96
11	8.9	8.2	8.4	6.0	7.0	6.5	9.1	7.0	9.0	6.2	7.54	7.65	7	1.22
13	3.9	3.4	1.8	2.5	3.5	3.2	5.1	3.5	3.0	3.7	3.25	3.45	3.5	.87
15	5.4	5.7	6.7	4.5	6.5	4.8	7.5	4.5	6.0	5.5	5.63	5.60	4.5	.99

\+ For magnitude estimation the geometric mean is used.
* When dual modes occur, the value given is midway between the two groupings.
** When no mode is present, the value is the median.

NOTE: Panel 3 was the standard, hence it is not in table (B).

TABLE 8

COMPACTNESS OF VERTICAL FOURIER THIRD HARMONIC

(A) RANKING

Panel	Rater or Test Subject										Average S.D. = .98			
	24	25	26	27	28	29	30	31	32	33	Mean	MDN	Mode	S. D.
1	1	1	1	6	1	1	1	1	1	1	1.50	1.06	1	1.35
2	2	2	2	4	7	2	2	2	2	2	2.70	2.12	2	1.64
3	8	8	9	9	9	9	8	9	8	8	8.50	8.50	8.5**	.53
4	11	10	10	11	11	10	11	10	9	10	10.30	10.30	10	.67
5	9	9	8	8	8	8	9	8	10	9	8.60	8.50	8	70
8	5	4	4	1	3	3	4	6	5	4	3.90	4.00	4	1.37
9	6	7	6	5	5	7	7	7	7	7	6.40	6.67	7	.84
10	3	3	3	2	2	4	3	5	4	3	3.20	3.10	3	.92
11	10	11	11	10	10	11	10	11	11	11	10.60	10.67	11	.52
13	4	5	5	3	4	6	5	3	3	5	4.30	4.50	5	1.06
15	7	6	7	7	6	5	6	4	6	6	6.00	6.10	6	.94

(B) MAGNITUDE ESTIMATION

Panel	Rater or Test Subject										Average S.D. = .79			
	24	25	26	27	28	29	30	31	32	33	Mean +	MDN	Mode	S. D.
1	3.0	2.0	1.8	6.5	2.0	3.3	2.5	3.0	2.5	4.0	2.85	2.75	2.50*	1.38
2	4.5	3.0	2.8	5.5	6.4	3.7	3.0	4.0	3.5	4.3	3.93	3.85	3	1.16
3	7.5	6.5	7.7	8.0	7.8	6.5	7.0	7.5	8.0	7.5	7.38	7.50	7.5	.56
4	9.6	8.0	8.2	9.0	9.0	7.1	8.0	8.5	8.7	8.4	8.42	8.45	8.50*	.69
5	8.0	7.5	7.5	7.5	7.0	6.1	7.5	7.0	9.0	8.1	7.48	7.50	7.5	.77
8	5.3	3.8	4.7	3.5	4.5	4.0	4.5	6.0	5.5	4.6	4.58	4.55	4.5	.78
9	7.0	6.0	5.7	6.0	5.8	5.8	6.0	6.2	7.5	5.7	6.15	5.97	6	.60
10	4.8	3.5	4.1	4.0	4.2	4.3	4.4	5.7	5.3	4.4	4.43	4.35	4.4	.64
11	9.3	8.2	9.0	8.5	8.3	7.5	7.7	9.0	9.5	8.5	8.53	8.50	8.75*	.66
15	6.1	5.3	6.4	6.8	6.3	4.7	5.2	5.5	6.0	5.3	5.73	5.75	5.3	.66

\+ *For magnitude estimation the geometric mean is used.*
* When dual modes occur, the value given is midway between the two groupings.
** When no mode is present, the value is the median.

NOTE: Panel 3 was the standard, hence it is not in table (B).

TABLE 9

CORRELATIONS BETWEEN RANKINGS AND MAGNITUDE ESTIMATES

OBSERVER	SPEARMAN RANK CORRELATION COEFFICIENT		
	GRID PHOTOGRAPHS	HORIZONTAL FOURIER	VERTICAL FOURIER
24	.808	.859	.884
25	.767	.777	.878
26	.936**	.887*	.924
27	.833	.604**	.871
28	.839	.786	.888
29	.682	.674	.750**
30	.736	.859	.795
31	.815	.794	.873
32	.651**	.871	.939*
33	.804	.700	.826
MEDIAN +	.810	.790	.876

* Maximum value in the column of numbers
** Minimum value in the column of numbers
\+ Half of all values exceed and half are less than the median in the columns of the table.

TABLE 10

CORRELATIONS BETWEEN MAGNITUDE ESTIMATIONS

OBSERVER	SPEARMAN RANK CORRELATION COEFFICIENT		
	GRID PHOTOs & HORIZ. FOURIER	GRID PHOTOs & VERT. FOURIER	HORIZONTAL FOURIER & VERTICAL FOURIER
24	.848	.744	.751
25	.889*	.920	.968*
26	.768	.903	.845
27	.871	.674	.656
28	.836	.582	.791
29	.802	.829	.835
30	.554**	.921*	.647
31	.705	.695	.642**
32	.627	.407**	.672
33	.887	.869	.851
MEDIAN +	.819	.786	.771

* Maximum value in the column
** *Minimum value in the column of numbers*
\+ Half of all values exceed and half are less than the median in the columns of the table.

Note the correlations in table 11 of ranks of grid photographs for distortion with ranks of horizontal Fourier pictures (.6745) and the r' of .0169 of magnitude estimations of grid photograph distortion with magnitude estimations of horizontal Fourier compactness. This latter value of .0169 is not significantly different from zero. Clearly, the magnitude estimates were inferior to the ranks of third harmonic compactness for predicting the judged optical distortion in the gridboard photographs. The corresponding correlations of .9504 for ranks and .1376 for magnitude estimations for the horizontal Fourier indicate that the same superiority of the ranks over the estimates hold for the vertical Fourier pictures. Rankings were appreciably better than magnitude estimations in predicting gridboard photograph distortion from either horizontal or vertical Fourier photographs. The expectation, before data collection, was that estimations might be superior to ranks. If the raters had been trained in making magnitude estimation judgments, the correlations might have been higher, but this is only conjecture.

TABLE 11

CORRELATIONS BETWEEN RATER AVERAGES

Gridboard Photographs G		Compactness of Fourier Third Harmonic			
		Distortion Rankings		Distortion Estimations	
Measure	Rankings	Horizontal H	Vertical V	Horizontal H	Vertical V
Estimations	.9773(10)	.8018(10)	.9656(10)	.0169(9)	.1369(9)
Rankings	...	.6745(11)+	.9504(11)+	.7855(10)	.9313(10)

NOTE: The number in parenthesis following the correlation coefficient is the number of pairs of averages that are used in the computation of the correlation coefficient. Since one "picture" is the standard (with a value of 5) in the magnitude estimations, and since the standard is not the same for vertical and horizontal Fourier pictures, the numbers in the parenthesis will vary from 9 to 11.

+Spearman rank correlation coefficients. The other correlation coefficients in the table are product moment correlation coefficients.

TABLE 12

CORRELATION OF FOURIER COMPACTNESS DATA WITH DISTORTION DATA FROM GRIDBOARD PHOTOGRAPHS

RANKS+				MAGNITUDE ESTIMATES++			
G-V	G-H	G-F*	G-F'	G-V	G-H	G-F*	G-F'
.9504	.6745	.9349	.9569	.1376	.0169	.0884	.0889

+The coefficients for ranks are Spearman rank correlation coefficients, based on 11 pairs of values.

++The coefficients for magnitude estimates are produce moment correlation coefficients, based on 9 pairs of values.

The value of F is (H+V)/2, i.e., the average of the horizontal and vertical Fourier means for each panel. The value of F' is calculated for the formula F' = AH + BV, where A and B are derived from a least squares calculation giving the optimum Fourier value for maximizing the G-F correlation.

KEY:G = Gridboard; V = Vertical Fourier; H = Horizontal Fourier; F* = The H-V Average, F' = Optimal H-V Composite.

A comparison of the compactness of the vertical Fourier third harmonic with the horizontal Fourier third harmonic for predicting distortion rankings is of some interest. Note in both the two distortion rankings columns and in the two distortion estimates columns that the vertical Fourier column has appreciably higher correlation coefficients than the horizontal Fourier column. This is true for all four comparisons in the table. The vertical Fourier photographs are more efficient than the horizontal Fourier photographs for either estimating or ranking judged grid photograph optical distortion. This superiority of the vertical Fourier pictures was also found in Experiment 1.

One might expect that since both vertical (V) and horizontal (H) Fourier data were correlated with gridboard photograph distortion (G) data, a composite of V and G might be superior to either alone. This expectation does not work out. The basis for this answer is found in table 12. With the 10 raters in experiment 2, the rank data yield essentially equal correlations between G and F with either equal V-H weights (F*) or with optimum weights (F'). Use of V alone is essentially as good as using a composite of V and H, and is appreciably better than use of H ranks alone for predicting gridboard photograph distortion rank (G). The same is true for magnitude estimation, except that the composite is essentially worthless, being even lower than V in prediction efficiency.

CONCLUSIONS FROM EXPERIMENTS 1 AND 2

• The subjective measurements have shown that optical Fourier analysis can be used with considerable effectiveness to measure the optical distortion of a distorting transparent panel. Since the Fourier method is effective, it would be worthwhile to develop an objective method for quantifying the "compactness" of Fourier harmonics. This study has shown that an efficient objective optical qualty assessment technique is possible.

• *In the present study vertical Fourier pictures, i.e., pictures made with vertical parallel target lines, were more efficient than* horizontal Fourier pictures in predicting the optical distortion of transparent distorting panels. Unequal but optimum weighting of vertical and horizontal Fourier harmonic compactness data to attain a composite Fourier rating may not be necessary. Use of only vertical Fourier data may be adequate. The use of vertical line targets only will have to be verified by experimentation with real aircraft windscreens. The decision should be arrived at after an objective Fourier "compactness" measure has been developed and applied to real windscreens.

• Magnitude estimation was decidely inferior to ranking, especially when data from several raters was averaged, for predicting optical distortion.

APPENDIX I

INSTRUCTIONS FOR EXPERIMENT 2

You will be given a set of pictures. Each picture shows several "blobs" or "smeared out" areas of light. One of the pictures is a standard or anchor that defines the center or "5" of a scale of *commpactness*, a scale that goes from 1 to 10. You will have two tasks: first to rank the pictures for compactness of the arrow-designated area, then to estimate the amount of compactness on a 10 point scale.

(A) Task 1: Ranking Compactness
Arrange these pictures from best to worst, "*Best*" meaning having the *smallest or most tightly packed* blob, and "Worst" having the largest or least tightly packed blob. The "blob" that you are to rank is marked with an arrow. Ignore the remainder of the picture. When you are finished, hand the stack of ordered or ranked pictures to the test administrator.

(B) Task 2: Estimating Amount of Compactness
Introduction
In Task 1 you arranged the pictures in order. In Task 2 you have to assign a number to each picture. The number indicates where the compactness of the designated area (or "blob") falls on a scale of 1 to 10. When you arranged the pictures in order in Task 1, you may have noticed that the difference in amount of distortion in adjacent pictures varied: some pairs differed by little, while others differed by an easily noticeable amount. Thus, the numbers that you assign to locate pictures on the compactness scale are unlikely to be whole numbers such as 1, 2, 3, etc. Numbers, such as 1.5, 1.7, etc., are more likely. As an example, if a picture falls barely above midway on the scale, it might receive a 5.1 or 5.2 etc.

Your Task
Take each picture, one at a time, and place it next to the standard picture. Examine both and assign a number to the unknown picture. This number is the *estimated degree of compactness.* It indicates where the picture falls on the 1-10 point scale whose center is established by the standard (or "5") picture. Hand the picture to the test administrator and give him your estimated compactness rating for it. Go on to the next picture, etc.

APPENDIX II

COMMENTS ON FOURIER ANALYSIS

The physicist, the mathematician and the engineer are familiar with Fourier analysis, as it is a tool that they frequently use. Most workers in other disciplines have not encountered Fourier analysis. The comments in this appendix are at an elementary level and are of interest only to those not familiar with the technique.

The basic notion of Fourier analysis is that any two-dimensional figure may be conceived of as consisting of a series of sine waves of different frequencies, amplitudes, and phases. Any figure may thus be "broken down" or analyzed into a series of such waves and, conversely, if such a series of sine waves is added together, the original figure is "reconstituted" or synthesized. Pictures, even simple line drawings, contain an infinite number of these sine waves. Analyzing a real picture or figure into sine wave components would be a prodigious task, even if only a few of the lower spatial frequency waves were broken out. Fortunately, a technique known as optical Fourier analysis simultaneously abstracts the sine waves over an entire picture. The equipment shown in figure 2 does this.

Suppose that a photograph is made of a test pattern composed entirely of straight parallel bars or stripes, with the space between bars being essentially black. If a device for measuring light intensity in a small area is scanned across one stripe, the output of the device will jump from essentially zero to a high value in coming onto the stripe from one edge, remain constant across the stripe, and fall to zero in passing the second edge. A plot of intensity against time or location of the scan would thus resemble the top and sides of a square or a rectangle. That is why a target composed of parallel straight stripes is called a square wave target. The square wave so produced in the plot of the output of the light intensity measuring device could be synthesized by adding together a large number of the proper sine waves.

If an optical Fourier analysis is performed on the picture of the parallel stripe or square wave target, there will exist in the Fourier or transform space a pattern of energy representing the spatial sine wave composition of the target. Distance out from the center represents the frequency. In the center, there will be a small central spot or energy concentration. There also will be a series of uniformly spaced "spots" at right angles to the stripes in the original picture of the target. These secondary spots represent harmonics or multiples of the basic optical spatial frequency of the square wave test target pattern. If the original photographs were taken of a parallel line pattern with an intervening windscreen between the camera and the gridboard, the thickness and straightness of the lines in the photograph would vary. This variation would cause variation in optical spatial frequencies and intensities. It would result in a spreading or smearing of the energy in the harmonic "spots." The more expensive the smearing, the greater the corresponding distortion in the windscreen.

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